VOL. II, No. 3
FALL-WINTER, 1954

PUBLISHED
QUARTERLY

RESEARCH TRENDS

CORNELL AERONAUTICAL LABORATORY, INC.
4455 GENESEE ST. BUFFALO 21, N. Y.

WIND TUNNELS HAVE WALLS

Wall Reflections Minimized in Transonic Testing By C.A.L. "Perforated" Tunnel

by KING D. BIRD

The first low-speed wind tunnels were built several years before the Wright brothers' first flight. More recently, the first wind tunnels capable of producing air speeds greater than the speed of sound (about 760 miles per hour at sea level temperature) preceded by several years the first supersonic flight carrying a human being. Virtually from the outset, tunnel development in the various speed ranges has tended to keep somewhat ahead of actual aircraft development as a result of the natural desire that the first flight of a new aircraft should not be its last.

Missiles and airplanes can be effectively engineered only if accurate data are available on precisely what happens when these objects move through the air.

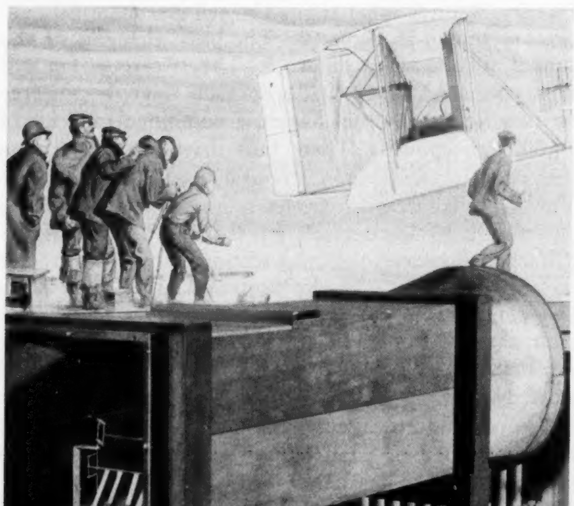

FIGURE 1 — A full-scale reproduction of the Wright wind tunnel in the Hall of Aviation of the Franklin Institute. In the background is a mural entitled "First Flight" by William Heaslip.

Since the very beginning of aeronautical research, such aerodynamic information has been obtained by holding a scale model of an actual aircraft still for measurement and moving a homogeneous jet of air past it at controlled speed. This jet of air is usually confined by the walls of a structure called a wind tunnel. The validity of tests run in a wind tunnel depends on the principle that moving air past a stationary model yields the same forces as those that would act on a model if it were moved through the air. Although the Wright brothers were not the first to employ such a device, they did build and use a wind tunnel in designing their first successful airplane. Wind tunnels have been widely used since, and now are conspicuous but commonplace fixtures on the landscape at most aeronautical engineering centers.

The Wright brothers' wind tunnel is shown in Figure 1. The circular section at the right acts as a shroud for the fan which draws air from left to right through the test section. The test section is the box-shaped portion in the photograph. A two-bladed fan, 24 inches in diameter and driven by a two-horsepower gasoline engine, produced a maximum wind velocity of 27 miles per hour.

INGENIOUS BALANCE SYSTEMS

Simple but ingenious balance systems or scales (constructed of hacksaw blades and bicycle spokes) were used in the Wright brothers' early tunnel to measure both the lift force on the wings required to support the weight of the aircraft and the drag force which had to be overcome by the thrust from the propeller. In early wind tunnels the support system for the model consisted of struts protruding up through the tunnel floor and attached to the lower side of the wings and fuselage. The struts were attached to scales outside of the tunnel

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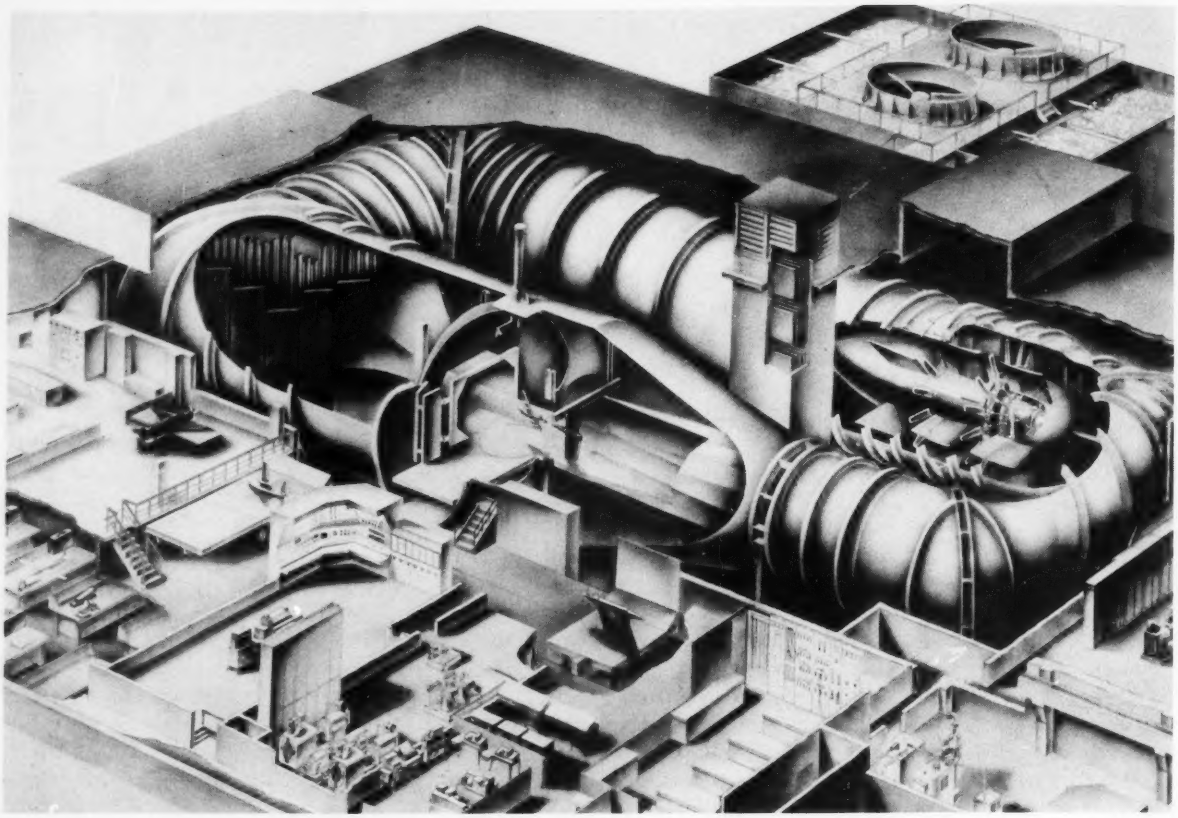


FIGURE 2 — The 12-foot Variable Density Wind Tunnel of Cornell Aeronautical Laboratory.

which measured the forces and moments acting on the model. Although such testing techniques quite naturally have been refined over the years, no major innovations for supporting the model or measuring the forces acting on it have been introduced until very recently.

THE COVER

What happens when a meteor enters the earth's atmosphere at 13 times the speed of sound, or 9,000 miles an hour? The photo-insert appearing at the left, as well as the top of the cover page, provides the answer by showing the intense heat generated at such speeds when air and body collide. In this photograph, a steel ball bearing, used to simulate the meteor, is being tested in C.A.L. hypersonic wind tunnel at a speed of approximately 9,000 miles per hour. The static temperature in the tunnel is minus 68 degrees, the normal temperature of the earth's stratosphere. As the air strikes the ball bearing, the impact heats it to incandescence and produces a temperature of about 6,000 degrees Fahrenheit, more than half the surface temperature of the sun. It is temperatures of this magnitude, produced by impact as the meteor enters the earth's atmosphere, that destroy the meteor before it reaches the earth. Although the duration of a test at this speed, Mach 13, in a 50-foot long shock tube is only about one millisecond, valuable aerodynamic information can be obtained on many of the problems involved in hypersonic flight. A future issue of RESEARCH TRENDS will carry a complete article on the Laboratory's hypersonic wind tunnel.

The modern high-speed wind tunnel is a far cry from its primitive ancestor with regard to size and complexity; yet its basic role is still to provide a controlled stream of air in which a scale model may be placed. One such modern tunnel is the 12-foot Variable Density Wind Tunnel at the Cornell Aeronautical Laboratory shown in Figure 2. The basic elements of this tunnel are shown in Figure 3. The two-stage fan system, consisting of 16 blades in each stage, is powered by two electric motors having a combined capacity of 14,000 horsepower. These fans drive the air around the tunnel circuit in a counter-clockwise direction. Through the large diameter sections of the tunnel, the air speeds are moderate. As the test section is approached, however, the cross-sectional area is contracted to only one-eighth of the upstream area. Because of this contraction, the air speed increases to about eight times its upstream value as it flows into the test section. At the end of the test section, the air is diffused or slowed down again (to prevent large energy losses) in the so-called diffuser section of the tunnel. This section is connected to the fan section giving a closed-circuit tunnel.

As simple as the basic principles and techniques involved in wind tunnel testing are, there is still an astonishing number of difficulties in building and operating a wind tunnel so as to measure only the interactions between airstream and the test model that duplicate those encountered in actual flight. Measure-

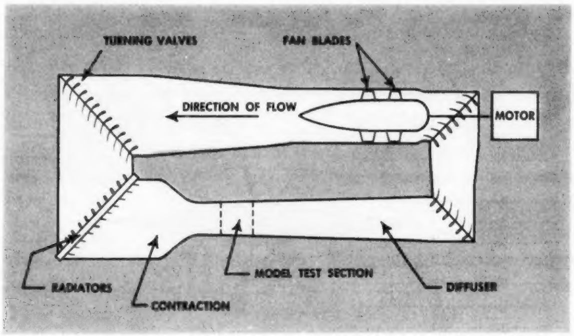


FIGURE 3 — The basic elements of a closed circuit wind tunnel.

ments must be uncontaminated by interactions between the airstream and the tunnel walls or the model support system, since effects of this type have no counterpart in ordinary flight.

TROUBLESOME TRANSONIC RANGE

These unwanted interactions, although a problem even in the very early days of the wind tunnel, were less serious than they are today, for test speeds were relatively low and test results were probably within the over-all precision of the measurements. As air speeds have increased, however, these interactions have usually become worse and they are particularly troublesome in the transonic speed range — just below, at, and slightly above the velocity of sound (700 to 900 miles per hour at sea level temperature). Only within the last decade have these problems become really acute enough to require that intensive effort be devoted to solving them. Although the interaction effects stemming from model support systems probably never will be entirely eliminated, they have been minimized by placing the model-support strut where it has the least effect — out the rear of the model. Along with this so-called sting-type support have come intricate, miniaturized balance systems using electrical strain gages mounted right inside of the test model itself.

The interaction effects contributed by the tunnel walls were not as easily remedied as was the interference problem posed by the model support system. For the past several years Cornell Aeronautical Laboratory, as well as a number of other organizations, has devoted substantial effort to obtaining a satisfactory solution to this problem. The Laboratory's work has culminated in what appears to be a major contribution to aeronautical research, the perforated-wall type of wind tunnel. Until very recently details of this new wind tunnel were classified for security reasons.

TWO-FOLD PROBLEM

Actually, the tunnel-wall interaction problem is two problems, for it has one specific character when the airstream has a velocity below the speed of sound (or is **sub**sonic) and a somewhat different character above the speed of sound (**super**sonic). The subsonic part may be understood by considering the "streamline" pattern around a wing. In free flight, pressure disturbances travel in all directions from a wing or airfoil shape at the velocity of sound, and in effect serve as a "make way" warning to the air that an object is approaching. The pressure impulses then literally cause the air particles to move out of the path of the wing as it approaches. Or, as in a wind tunnel, where the air rather than the body is in motion, the air moves smoothly around the wing as shown by the streamline pattern of Figure 4a. In the conventional wind tunnel, the walls prevent the streamlines from taking this shape, since there can be no flow through the solid walls. Consequently, the streamlines become squeezed together by the effect of the tunnel wall, and a flow pattern like that shown in Figure 4b results. This creates pressures and velocities over the model which differ from those that would be encountered in actual flight.

UNWANTED INTERACTION

One might ask why the walls cannot be removed from the tunnel in the test section region, permitting

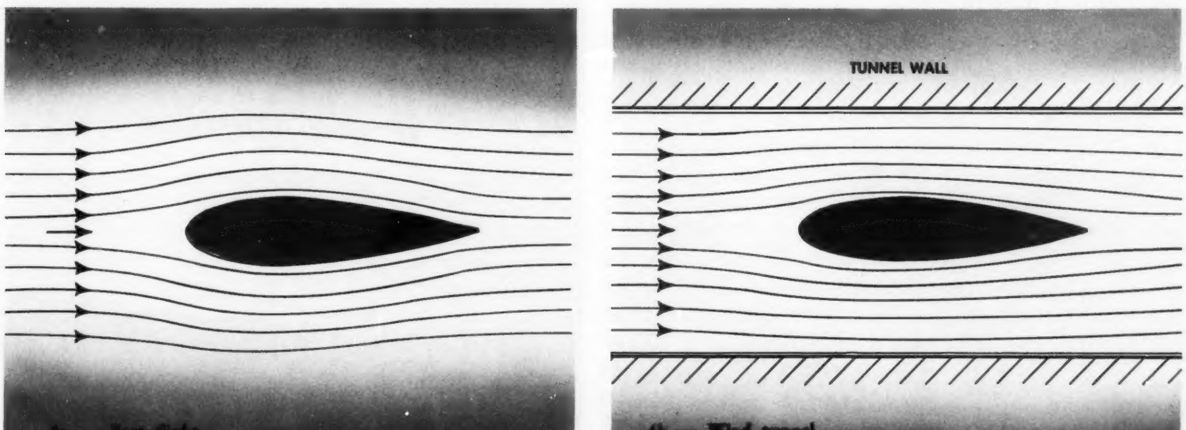


Figure 4 — The streamline pattern of airflow around a wing at subsonic speed. Note how streamlines in the photograph at the right become squeezed together by the tunnel wall.

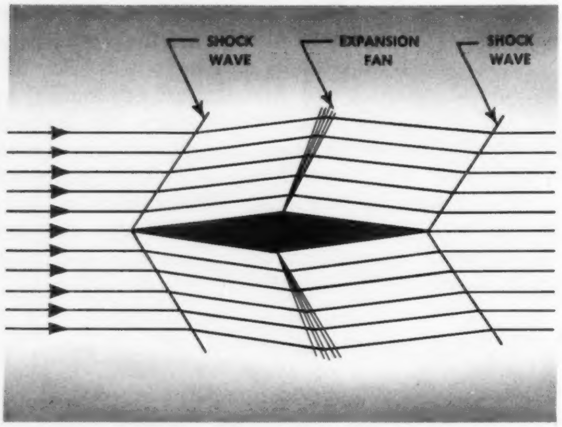


FIGURE 5a — Pattern of airflow around a diamond-shaped wing section in free flight at supersonic speed. Note the abrupt change in direction of the streamlines.

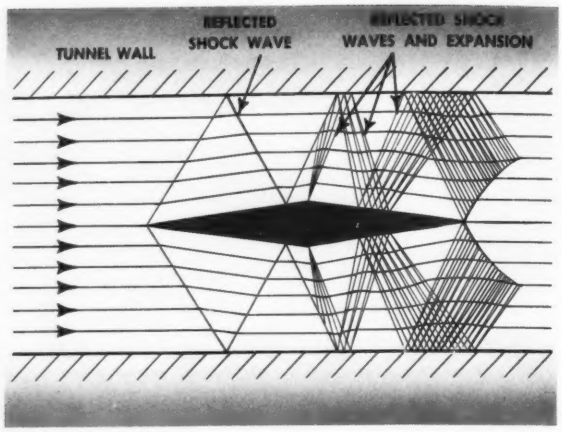


FIGURE 5b — Pattern of airflow around a diamond-shaped wing section in a supersonic wind tunnel. Note the complex shock wave reflections due to the tunnel walls.

the streamlines to again curve around the body as in free flight. Removal of the walls, however, still does not simulate the conditions of free flight because the air outside of the jet is at rest with respect to the model, whereas in actual flight the aircraft is in motion with respect to all of the air. In spite of the lack of free-flight similarity, the interactions due to the tunnel walls or the boundary of still air at the exit of the jet are highly significant. With the open jet the streamlines around the body adjust themselves until there is no difference in pressure across the boundary between the still air and the jet, for such a boundary cannot support a pressure difference. When this condition has been realized, it is found that the streamlines actually become **dilated** from the free-air pattern, rather than constricted as was the case for the solid wall tunnel.

NEW APPROACH

The fact that the interactions are of an opposite character suggests that a wind tunnel with partially open and partially closed boundaries might be employed to give a configuration with interactions which cancel one another, and therefore yield a net interaction of zero at the test model location. This was precisely the thinking of researchers at the National Advisory Committee for Aeronautics (NACA) at Langley Field, Virginia, who announced in 1948 that effectively zero interaction had been shown to be possible both theoretically and experimentally. The configuration proposed by the NACA was the so-called slotted throat, which consisted of alternate walls and slots (open sections) running in the direction of airflow. This disclosure by the NACA was of considerable importance. Although it offered a direct solution to only the subsonic portion of the problem, it was a big start in the right direction.

It was noted above that in subsonic flow the presence of a body moving through the air is detected upstream by pressure disturbances which travel at the velocity of sound. Thus, the air is able to make an adjustment in anticipation of the approaching body, with a resulting smooth flow around the body. In supersonic flow, pressure waves continue to emanate in all directions from the body at the velocity of sound. Because the body itself is traveling at a velocity greater than that of sound, it is clear that the approach of the body cannot be telegraphed upstream in this case. As a result there is no warning, and a direct collision takes place as the body and pressure waves from the body come into contact with each fluid particle in the path. In general, a conical-shaped wave front called a shock wave is produced. Through the narrow wave front, very large changes in pressure and velocity of the air occur which are, to all practical intents, effectively discontinuous. Thus, at supersonic velocities, as a body moves through the air (or in the wind tunnel, as the air moves past the body) the air does not adjust itself into a smooth streamline pattern around the body. Instead, the flow assumes a pattern such as that shown for a supersonic wing section in Figure 5a. It can be seen that the flow is turned in direction abruptly as it passes through the shock wave. Now if a wind tunnel wall is placed along the flow as shown, the air, not being able to pass through the wall, must turn back parallel to it. As in the situation described above, the air, because it is moving faster than the speed of sound, is unable to sense the presence of the walls until they are actually reached. Thus another shock wave is formed as shown in Figure 5b. This shock wave acts quite literally like a reflection of the main shock wave, and the angle of reflection is essentially the same as the angle at which the main shock wave strikes the tunnel wall. If the path of the reflected shock wave leads back onto the test model, an interaction between model and tunnel wall arises which has no counterpart in free flight. These interactions can be large, and there is no known method by which the test data may be corrected to account for them. It is apparent that under such conditions valid results cannot be obtained from wind tunnel tests.

STEEP SHOCK WAVES

One might suggest that models be used which are short enough to permit the reflected shock wave to pass

behind the model. This is exactly what is done at the higher supersonic Mach numbers. (Mach number is defined as the ratio of air speed to the speed of sound.) As the velocity comes closer to the speed of sound, however, the shock wave from the nose, and hence its reflection, becomes steeper and steeper and therefore the allowable model length becomes shorter and shorter. In fact, as sonic speed is reached, the allowable model length approaches zero. Consequently some method for eliminating these reflected shock waves had to be found before testing could become practical in the low supersonic range.

EXPANSION WAVES FORM

As in the subsonic case, one might consider removing the walls entirely. Again, however, strict similarity with free flight still is not achieved. Once more the flow will readjust itself until there are no pressure differences across the boundary. In passing through a shock wave, the air is compressed — that is, the pressure increases. To maintain a constant pressure along the boundary of the jet, it follows that the flow downstream of the shock wave must be expanded to the initial pressure upstream of the shock wave. This expansion requires the flow to turn away from the model and the turning is accompanied by the formation of a fan of expansion waves. These expansions may also be transmitted back towards and across the model. In other words, if the wall is removed, the incident shock wave is reflected not as a shock but as a series of expansion waves, which again result in unwanted interactions on the model. It is worthy of note that the characteristics of an expansion wave are opposite to those of a shock wave; and it is again suggested that a partially open, partially solid wall might make shock waves reflected from the tunnel walls act as part shock and part expansion waves in such a manner that one would effectively cancel the other and yield zero interference at the model.

The slotted-wall wind tunnel referred to before is, in fact, a possible combination. Because of the sharply discontinuous nature of disturbances in a supersonic stream, however, the large alternate solid and open sections of the slotted wall result in alternate compressions and expansions, which do not merge and self-cancel and are reflected back to the model. The Laboratory in its approach to the wave cancellation problem reasoned that the use of a porous wall, that is, a wall having continuously distributed open and closed sections rather than one having discrete, large-scale open and closed sections, would result in coalescence of the reflections close to the wall and yield a considerable attenuation of the reflected disturbances at the model location.

The major practical difficulty to be faced was that materials most nearly simulating truly homogeneous porous walls, such as sintered bronze or fine-mesh screens, were not considered usable as structural materials for large wind tunnels. It seemed possible however, to achieve a practical solution to this problem by using perforated metal sheets for the tunnel walls, if care was taken to keep hole spacing small in comparison with over-all dimensions of the test section.

"PERFORATED" WIND TUNNEL

To determine the validity of this reasoning, a small-scale test section (2¼ by 4-inches in size) was constructed at Cornell Aeronautical Laboratory in 1950. Sintered bronze sheet and screens were tested to give results for the homogeneous porous case, while commercial perforated metal plate was used as a practical wall material. The general line of reasoning was borne out by the experimental results.

Figures 6a and 6b are schlieren photographs of the flow in this perforated-wall wind tunnel at subsonic

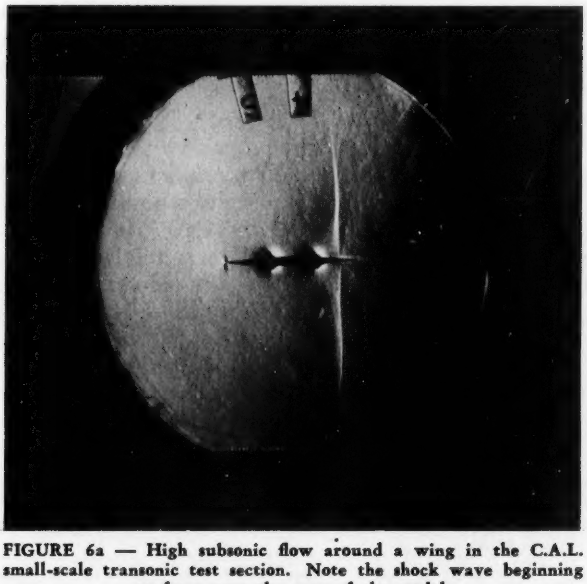


FIGURE 6a — High subsonic flow around a wing in the C.A.L. small-scale transonic test section. Note the shock wave beginning to form over the rear of the model.

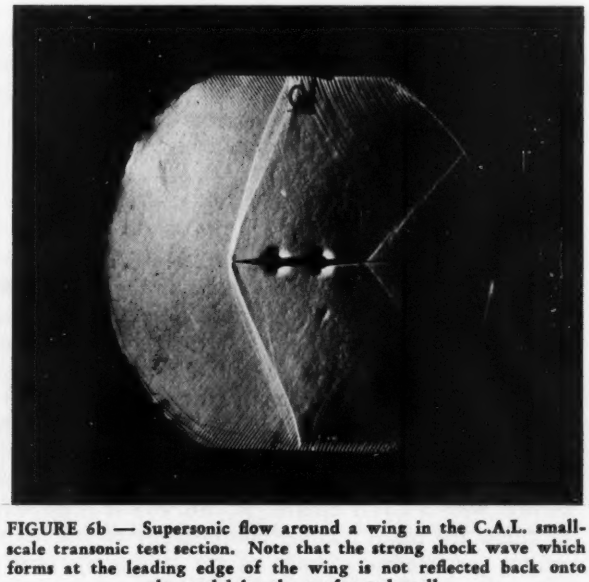


FIGURE 6b — Supersonic flow around a wing in the C.A.L. small-scale transonic test section. Note that the strong shock wave which forms at the leading edge of the wing is not reflected back onto the model by the perforated wall.

and supersonic velocities. The shock wave pattern is made visible in these photographs by using a special photographic technique (schlieren). This technique is based on the principle that differences in air density in the flow field produce different degrees of refraction of light rays passing through the flow. The supersonic example, taken at a Mach number of 1.26, shows a shock wave from the leading edge of the wing. It will be noted that it strikes the wall, but there is no evidence of a reflection back to the model. Along the wall, a number of very small alternate light and dark areas are present. These are alternate shock and expansion waves which emanate from the holes themselves in the perforated walls. These small wavelets coalesce in the proximity of the wall so that the net disturbances are negligible at the model.

THE SONIC PROBLEM

Beyond effecting some measure of solution to the wall interaction problem, the perforated-wall tunnel has offered a solution to a secondary problem. Up to velocities close to Mach number one, control of the air speed is relatively simple. To increase the air speed, the fans may be run faster or the pitch angle of the fan blades may be increased. Either of these methods is satisfactory, and both do essentially the same thing: establish a difference of pressure around the wind tunnel circuit. This pressure difference results in accelerating forces on the air which drive it around the circuit. But this kind of direct mechanical push will not produce air flow faster than sound. In order to reach supersonic velocities, not only must there be an adequate difference in pressure in the tunnel but the flow must be channeled through a converging and then diverging section known as a Laval nozzle. It is characteristic that sonic velocity is reached at the minimum cross-sectional area or throat of the nozzle. The supersonic Mach number reached downstream has a unique value for any given ratio of throat area and downstream area. Conversely, a different area ratio is required for each Mach number. Thus, individual nozzles or a nozzle that can be adjusted to give different area ratios is required for each supersonic velocity. In either case the expense is enormous and the mechanical equipment troublesome at best.

VERSATILE TEST SECTION

This necessity of having many different test sections or an adjustable test section is avoided in the perforated-wall transonic tunnel. By surrounding such a test section with a large tank or plenum chamber, and removing air from the plenum with a suction pump, air can be pumped from the test section through the perforations (or slots) and out of the tank. It can easily be seen that pumping air from the main stream is exactly equivalent to expanding the area of the test section with a Laval nozzle. In this way it is possible to adjust the Mach number continuously to any value within the operating range of the tunnel by simply controlling the amount of air pumped from the plenum.

At the conclusion of the successful experiments in the small-scale tunnel, plans were made for the ultimate conversion of the Laboratory's 12-foot Variable Density Wind Tunnel to a perforated-wall, auxiliary-pumped transonic tunnel.

EXPERIMENTAL CONFIRMATION

Because formidable engineering problems were associated with this conversion, and because it was deemed highly desirable to have a backlog of test results by which to assess the practicality of the tunnel, effort was centered on the construction of a relatively inexpensive interim 4-foot transonic section which could be inserted in the main stream of the 12-foot variable density wind tunnel. This transonic tunnel was made available to the aircraft industry for research and developmental testing in February 1953. In spite of the fact that many questions concerning transonic testing remained unanswered at that time, its acceptance by the industry was immediate. By the end of the first year and a half, over 1,800 contract hours of testing had been logged in this test section. The very considerable body of data secured from tests run on a wide variety of aircraft configurations has been an important factor in confirming the existing theoretical results. Its greatest value has been to provide qualitative insight into those areas which have been resistive to theoretical analysis. Each empirical result by itself is, of course, not conclusive. In organized total, however, the data provide a strengthened theoretical basis for effective design of a perforated-wall transonic wind tunnel.

$2,000,000 MODERNIZATION PROGRAM

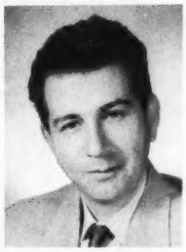
Although the early work aimed at establishing the feasibility of the perforated-wall type transonic tunnel was done as Laboratory-sponsored research, the Air Force has supported subsequent development effort on the tunnel both at Cornell Aeronautical Laboratory and elsewhere. Currently, a $2,000,000 program for the conversion of the Laboratory's 12-foot Variable Density Wind Tunnel is under way that will provide a new 10-foot transonic test section capable of operating over a Mach number range that is continuously variable from 0.85 to 1.25. This test facility should be available to the aircraft industry early in 1956. We believe that this new tunnel will play an important role in helping to meet the aircraft industry's ever mounting demand for the detailed transonic data that are so vitally needed for the successful design of today's aircraft.

AVAILABLE REPORTS

"Development and operation of the C.A.L. perforated-throat transonic wind tunnel," Flax, A. H.; Ross, I. G.; Kelso, R. S. and Wilder, J. G., Annual Summer Meeting of the Institute of the Aeronautical Sciences (June 1954).

Description of C.A.L. variable density wind tunnel, C.A.L. Report WTO-080

FLUTTER



Flutter Can Cause Swift Destruction of Modern High Speed Aircraft

by WALTER P. TARGOFF

In the early days of flight, the flutter problem posed few questions to the aëronautical engineer and, indeed, little thought was given to it. As the size and speed of aircraft mounted, however, the problem became more serious. For low speed airplanes the use of ordinary static structural design methods was sufficient to insure freedom from flutter. With the advent of high performance aircraft, this very desirable state of affairs proved to be no longer true.

Although theoretical investigation of the aerodynamic forces on an idealized airfoil in flutter was undertaken as early as 1923, even today there is no rigorous theory that permits accurate computation of these forces on practical modern wings. This lack of a completely satisfactory theory has led to intensive experimental effort being devoted to the solution of the flutter problem. The NACA, the Armed Forces and various private aircraft companies have all undertaken broad experimental programs in the field. The Cornell Aeronautical Laboratory has also been a principal contributor in the work.

There are various basic means of obtaining experimental flutter information. Models can be mounted in wind tunnels, on rocket-propelled sleds, or on the wings of airplanes and tested at various velocities to ascertain the "critical flutter speed." This is the speed at which transient vibrations are neither damped out nor self-magnified, but instead persist at constant magnitude.

One apparently obvious way of getting data is to fly an airplane at its critical flutter speed and record what happens. Unfortunately this technique is not as simple to accomplish as it appears. It must be remembered that flutter is very often of an "explosive" character and the transition from normal flight to violent, destructive oscillations may occur in less than one second. A change in aircraft forward speed of only a few miles per hour may be sufficient to trigger off destruction. Consequently the test pilot must creep up on the critical flutter speed as he would stalk a wild animal.

What is FLUTTER?

In normal flight the wings and tail surfaces of an airplane are subjected to almost continuous disturbances by random aerodynamic forces. Such things as wind gusts and pilot course corrections put temporary loads on these surfaces. As with every elastic body such loads cause deformations of the airplane structure, and at the time of application and removal of the forces induce transient vibrations in the body. Ordinarily these vibrations are highly damped; that is, they disappear rapidly.

Under certain adverse design and speed conditions, however, this "damped" type of vibration does not occur but instead a self-magnifying oscillation arises. In this case, after the initial disturbance, each successive vibration becomes of larger and larger amplitude. After a short time, sometimes very short indeed, these oscillations can become dangerously large and may lead to structural failure. Subject to certain technical restrictions this type of self-enhancing vibration is called "flutter."

There are certain changes in aircraft behavior slightly below the critical flutter speed, however, which forecast the danger awaiting at somewhat higher speeds and, with the exercise of extreme caution, flight flutter tests may be performed.

In 1936 the Germans carried out a systematic flight flutter program on various models of the Junkers airplane. In the course of these tests one airplane, a Junkers JU90, was lost when violent, uncontrollable flutter occurred at a speed of approximately 310 miles per hour. In the JU90 tests, approach to critical flutter speed was made in increments of roughly 15 miles per hour. In 1937 the Glenn L. Martin Company undertook a series of flight flutter tests, first on an early version of the Martin Clipper and later on others of its large ocean transports. During the early days of World War II, C.A.L., then the Curtiss-Wright Research Laboratory, carried out a flight test investigation of wing and tail flutter on the Curtiss-Wright SB2C Hell Diver and an investigation of wing flutter on the Chance Vought F4U-1 Corsair. The Corsair was being equipped with one of the early wing-rocket-launcher installations and concern had been expressed that this addition might adversely affect the flutter speed. Tests

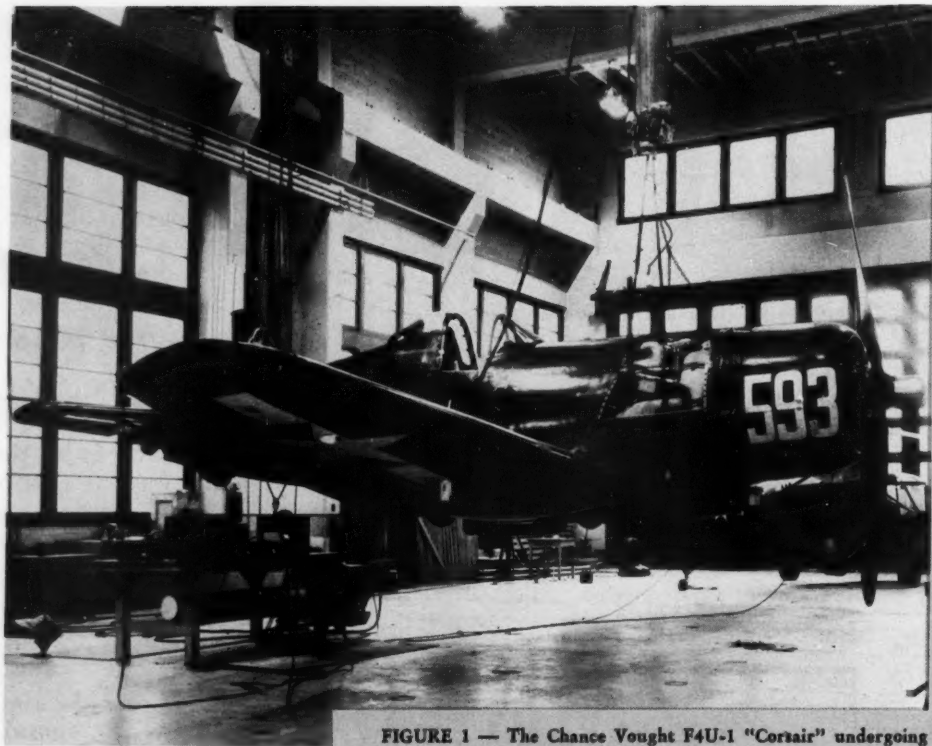


FIGURE 1 — The Chance Vought F4U-1 "Corsair" undergoing vibration tests during one of the Laboratory's early flutter investigations.

demonstrated that even with the wing-mounted rocket launcher the flutter speed was above the maximum operating speed of the airplane. The Hell Diver tests also failed to reveal flutter, and it was found later that the structural failures which had prompted the tests had been caused by compressibility rather than by flutter effects.

INADEQUATE THEORY

It is worthy of note that in a subsequent series of flight tests on another model of the SB2C flutter was not encountered even in flights made up to 150 per cent of the computed flutter speed. The negativeness of this result was in itself significant because it pointed up the inadequacy of the unsteady aerodynamic theory for predicting control-surface flutter. Actually, it was at once an important and unwelcome finding, for of all cases of flutter experienced on airplanes those involving control surfaces are by far the most numerous.

In 1945 C.A.L., under the sponsorship of the then Army Air Force, undertook a pioneering experimental program to measure the oscillatory air loads on a wing of infinite aspect ratio (very long, narrow wing) carrying both flap and tab control surfaces. Significant differences were found between the experimental forces and those predicted by the existing theory, especially for those forces induced by tab motion.

After the successful completion of the infinite aspect ratio tests, the Wright Air Development Center (WADC) sponsored research at C.A.L. aimed at obtaining similar data for wing-flap-tab combinations of low aspect ratio (wing span and chord of approximately equal dimension). This project was successfully completed in 1953. As with most of our work in the field of flutter, specific results of this program are so classified as to prevent discussion here.

Although often complicated by having many parameters inextricably interrelated, the study of models in an actual state of flutter has been found, in the main, to be the most feasible method for obtaining insight into the mechanism of flutter. In this method of research, models are built which simulate all or some of the dynamic properties of a typical airplane aerodynamic surface. These models are then tested in the wind tunnel to observe the effect, on flutter speed, of the change of certain of their physical characteristics. Much of the flutter research at C.A.L. has been of this type.

FLUTTER MODEL TESTS

An interesting program of this kind began with theoretical flutter investigations which showed that relatively low flutter speeds may result when sufficient "mass coupling" between two degrees of freedom exists and when the natural resonant frequencies of these two degrees of freedom are nearly equal. As an example we can imagine a wing that is free to vibrate in, say, bending and also free to vibrate in torsion, both motions having about the same resonant frequency. If the mass (weight) of the wing is so distributed that translational accelerations, due to the bending vibration, induce torsional or rotational deformations, and vice

versa, a pronounced susceptibility to flutter is theoretically predicted. Analyses made by several aircraft companies and the WADC showed that a frequency ratio near unity could occur for some particular aircraft designs. In several cases, flutter at speeds below the limit of the airplane's diving speed was indicated by theoretical calculations. Under WADC sponsorship, therefore, C.A.L. undertook a research project, completed in 1951, which was aimed at providing experimental evaluation of some of the important assumptions necessary to flutter calculations of such configurations without resort to flight flutter tests.

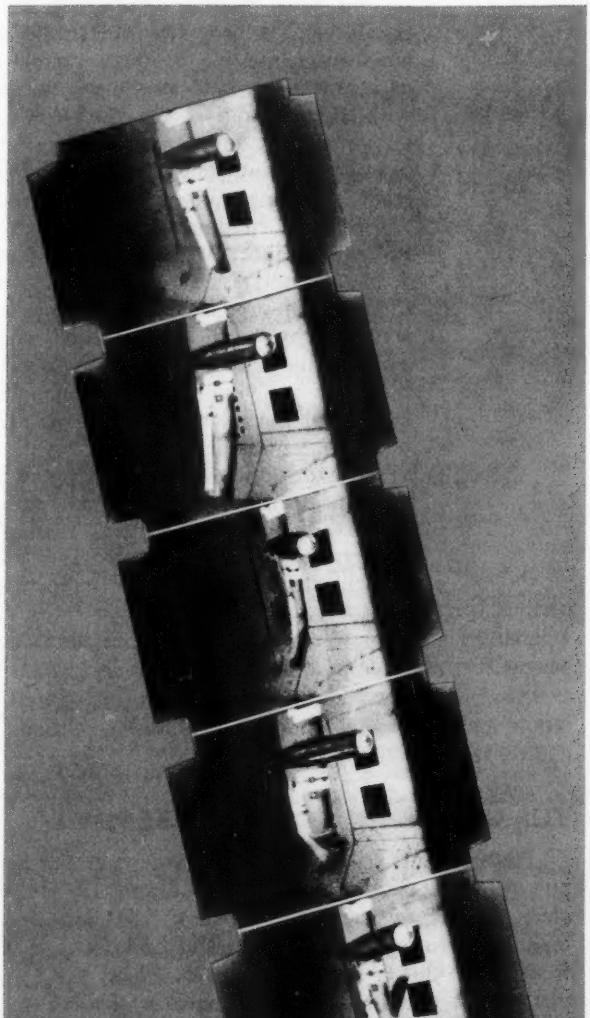


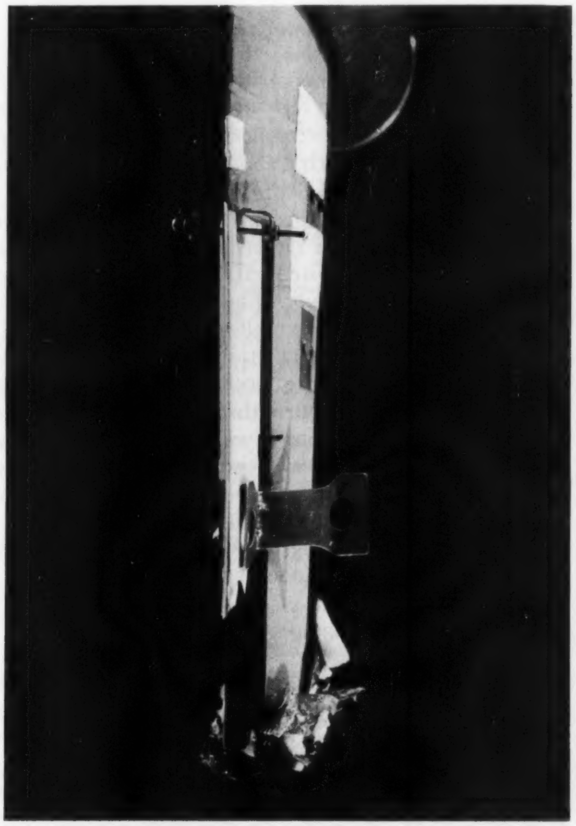
FIGURE 2 — Movie sequence depicting the almost instant destruction of a wind tunnel model as flutter is encountered. The time between the first exposure and the last is about one-tenth of a second. At the right is a still photograph of the model as it appeared when the tunnel was shut down. Destruction occurred with an increase in tunnel speed of only one-half mile per hour.

Besides providing experimental verification of theoretical trends, this program demonstrated that special corrections were necessary to the usual non-stationary aerodynamic theories to secure reasonable agreement between experimental and computed data. Marked differences were found in the flutter speeds for different models of nominally identical construction. It appeared that such differences can be expected whenever the bending and torsion frequencies are nearly equal and that extreme care must be exercised in the interpretation of flutter model test data for application to full-scale prototypes.

SUPERSONIC FLUTTER

One of the configurations tested in this program resulted in the "explosive" type of flutter previously mentioned. Three models were destroyed in the attempt to obtain data for this one flutter point despite the most painstaking care in the approach to the critical speed. Figure 2 shows a strip of movie film of one of these models undergoing flutter. The time between the first exposure and the last is about one-tenth of a second.

Development of high speed aircraft has spurred the investigation of flutter at supersonic speeds. In a program, sponsored by the WADC, C.A.L. undertook to make a rather exhaustive experimental survey of the flutter characteristics of an infinite aspect ratio airfoil at Mach number 1.72. The basic purpose of the program was to accumulate data at this Mach number



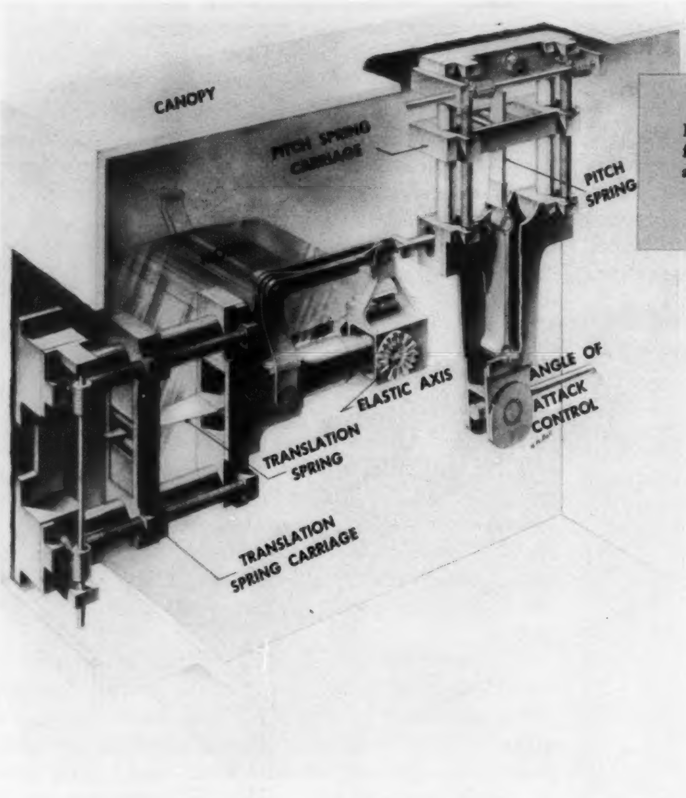


FIGURE 3 — A sketch of the test apparatus used for remotely controlling the flutter model's mass and stiffness parameters during supersonic wind tunnel tests at Aberdeen Proving Grounds.

to show the effects of systematic variation of all mass and stiffness parameters on models with and without ailerons. Tests were performed in the Bomb Tunnel of the Ballistics Research Laboratory at the Aberdeen Proving Ground during September 1951.

Because of the necessity of obtaining many data in a relatively short time, a rather elaborate test apparatus was employed. This system permitted wide variation of mass and stiffness values to be made by remote control without shutting down the tunnel. Figure 3 is a sketch of the tunnel installation illustrating some of the important parts of the mechanism. Within a one-week testing period, more than 300 distinct flutter points were obtained over a wide range of important parameters. These tests were noteworthy also because they included the first observed cases of supersonic aileron flutter. By virtue of the efficient flutter brake employed, the entire program was accomplished without the loss of a single model.

TIP PODS INFLUENCE FLUTTER

The increasing use of large tip pods on aircraft in recent years has made the consideration of the flutter effects of such tip pods more and more important. Not only does the weight of such tip pods introduce unusual vibration characteristics, but the shape of these pods may cause significant aerodynamic effects.

We have recently completed, for the WADC, a program involving the wind tunnel testing of flutter models of both straight and sweptback wings with large tip pods. These models were tested in three different conditions of fuselage restraint. The simplest of these, from a vibration point of view, is the "cantilever" condition in which the fuselage's support permits it no motion at all. Flutter test data obtained with this type of support do not duplicate actual flight conditions but they do permit study of the unsteady aerodynamics in a very satisfactory manner because of the relatively simple nature of the flutter modes involved.

The other two types of fuselage restraint permitted the so-called "symmetric" and "antisymmetric" fuselage degrees of freedom which simulate actual free-flight conditions. The former permits the fuselage to pitch and translate laterally at will, all other motions being precluded, while the latter permits only freedom in roll about the longitudinal axis of the fuselage. These three motions (pitch, translation, and roll) are commonly called the "rigid body" degrees of freedom.

THE UNCERTAIN TRANSONIC REALM

Flutter points were obtained for wide ranges of tip-pod weight, and weight distribution. Important results were obtained regarding the effects of these pod properties and the influence of the rigid body degrees of freedom on flutter speed. To a great extent the complexities of the mechanical peculiarities of these two apparently independent factors were delineated and explained.

Today, in flutter, as with most other aerodynamic phenomena, a realm of great interest and uncertainty is the transonic regime. Adding the additional complexities of unsteady conditions to the already confused problem of near sonic aerodynamics creates a situation that permits no easy theoretical solution. At present, at this Laboratory, there are two programs under way aimed at obtaining empirical understanding of this problem.

Rigorous scientific experimentation with large-scale flutter models at transonic speeds has involved difficul-

ties more formidable than anticipated. In one of these programs three models have been swept down the wind tunnel to destruction. Each of these losses has been due to a different cause and only one of the models was destroyed by the violent oscillations of flutter. Testing is scheduled to be resumed shortly and will demonstrate whether all sources of trouble have been eliminated.

In summing up our present knowledge of flutter, it appears that the growth of theoretical background is being outstripped by the rapidly advancing speed frontier. Certainly, no true solution to many present and future design problems can be obtained until a sound theoretical understanding of high speed, low aspect ratio, unsteady aerodynamics is available. It appears, however, that for the present and quite likely a good way into the future, we will have to rely on empirical or semi-empirical criteria to design our aircraft from a flutter viewpoint. Thus aeronautical engineers can look forward to "riding the tiger" of flutter research for some time to come.

REPORTS

"Aileron reversal research of straight and swept wings at high subsonic speeds," Goland, L., C.A.L. Report SB-569-S-2

"A method for calculation of airforces on oscillating finite wing," Reissner, E., C.A.L. Report SB-76-S-2

"Compressibility effects in flutter," Reissner, E. and Sherman, S., C.A.L. Report SB-240-S-1

"Control surface oscillatory and stationary aerodynamic coefficients measured on rectangular wings of low aspect ratio," Beals, V. and Targoff, W. P., WADC TR 53-64

"Flight flutter tests of the Chance Vought F4U-1 airplane," Cheilek, H. A., Pancu, C. D. P., and Weichsel, H., C.A.L. Report SB-348-S-2

"Flutter at M = 1.72, two-dimensional model tests," Andreopoulos, T. C. and Targoff, W. P., WADC TR 53-306

"Flutter model tests of wings carrying heavy tip pods — Part 1 straight wings," Brady, W. G., Loewy, R. G. and Targoff, W. P., WADC TR 53-161

"Flutter model tests of wings carrying heavy tip pods — Part 2 swept wings," Brady, W. G., Maier, H. G. and Targoff, W. P., WADC TR 53-161

"Measurements of the aerodynamic hinge moments of an oscillating flap and tab," Andreopoulos, T. C., Cheilek, H. A. and Donovan, A. F., USAF TR 5784

"Model SB2C-4 airplane flight flutter investigation rudder mass balance," Frissel, H. and Weichsel, H., C.A.L. Report SB-355-S-4

"The effect of engine locations on the antisymmetric flutter mode," Andreopoulos, T. C., Chee, C. F. and Targoff, W. P., AFTR 6353

"Wind tunnel corrections for the two-dimensional theory of oscillating airfoils," Reissner, E., C.A.L. Report SB-318-S-3

About the Authors...

KING D. BIRD, although only thirty, heads the Operations Branch of C.A.L.'s 12-foot Variable Density Wind Tunnel, one of the busiest and most versatile tunnels in the country. He is responsible for all phases of the engineering, planning and testing of models in the C.A.L. tunnel which is currently operating at a rate of over 4,000 test hours a year on a three-shift, six-day-week basis. The tunnel program is highly varied and includes tests of aircraft and missiles, supersonic propellers, bombs and projectiles, flutter models, and the calibration of airborne instruments. The speed range includes the subsonic, transonic and supersonic regimes.

Mr. Bird joined the Laboratory in 1951. He has been active in the design, calibration and evaluation of the four-foot perforated wall transonic wind tunnel. At present he is responsible for the aerodynamic work done in connection with the $2,000,000 modernization of C.A.L.'s tunnel for transonic testing.

Prior to joining the Laboratory he was an associate engineer working on the design of guided missiles at the Applied Physics Laboratory of The Johns Hopkins University. In 1946 he was employed by the Aircraft Laboratory at the Wright Air Development Center.

Mr. Bird received a bachelor's degree in Aeronautical Engineering at Rensselaer Polytechnic Institute in June 1946. He is a member of the Institute of the Aeronautical Sciences and is a representative of the Laboratory in the Supersonic Wind Tunnel Association.

WALTER P. TARGOFF has wrestled with the problem of flutter and vibration for 15 years and still finds it an unpredictable and nerve-racking business. Thus far he admits to having escaped the psychiatrist's couch, but he makes no prediction about tomorrow. In light of some of the baffling problems he is currently encountering on a transonic flutter program, such reticence probably stamps him as a man of considerable discernment.

Mr. Targoff heads the Applied Mechanics Section of the Aero-Mechanics Department and has been with C.A.L. for five years. He has played an important role in many of the accomplishments that have marked the Laboratory's ten-year effort in the flutter field. Prior to joining the Laboratory he headed the vibration analysis group at the Glenn L. Martin Company in Baltimore for three and a half years. He also spent five and a half years in the vibration section at the New York Navy Yard in Brooklyn, and was in the design section of the Navy Bureau of Ordnance in Washington for one year.

He received his bachelor's degree in Mechanical Engineering from City College of New York in 1939 and his master of science in Engineering from the University of Buffalo in 1952.

Among his other accomplishments, Mr. Targoff is the author of two important flutter articles: one is entitled "A Tabulation Method for the Calculation of the Critical Speed of Wing Divergence"; the other, "The Association Matrices of Bending and Coupled Bending Torsion Vibrations."

He is a member of the Institute of the Aeronautical Sciences, Tau Beta Pi, and Sigma Xi.

Recent C. A. L. PUBLICATIONS

Requests for copies of the following unclassified reports should be directed to the Editor

"A NEW SHOCK TUBE TECHNIQUE FOR THE STUDY OF HIGH TEMPERATURE GAS PHASE REACTIONS," Glick, H. S.; Squire, W. and Hertzberg, A., Fifth International Combustion Symposium, Pittsburgh, Pa. (September 1954)

This paper describes a modified shock tube developed for the study of high temperature chemical kinetics.

"A PROGRAM FOR FURTHER RESEARCH BY CORNELL AERONAUTICAL LABORATORY ON THE SPECTRA OF ATMOSPHERIC TURBULENCE APPLICABLE TO AIRCRAFT," Koegler, R. K., C.A.L. Report FRM 210 (16 pages)

The status of C.A.L.'s past research as well as a proposed future program into the nature of atmospheric turbulence spectra for application to aircraft and missile problems is outlined.

"APPARATUS FOR CONDUCTING HIGH TEMPERATURE CREEP STUDIES UNDER DYNAMIC LOAD CONDITIONS," Gillig, F. J.; Guarnieri, G. J. and Yerkovich, L. A., First International Instrument Congress and Exposition of the Instrument Society of America, Philadelphia, Pa. (September 1954)

This paper deals with the problems involved in the high temperature creep testing of metals in which pulsating tensile stresses are superimposed upon static tensile stresses at frequencies ranging from 11.5 to 15,000 cpm. Apparatus for conducting such tests is described and its operation discussed.

"DETERMINATION OF THE EXTERNAL CONTOUR OF A BODY OF REVOLUTION WITH A CENTRAL DUCT SO AS TO GIVE MINIMUM DRAG IN SUPERSONIC FLOW, WITH VARIOUS PERIMETRAL CONDITIONS IMPOSED UPON THE MISSILE GEOMETRY. PART III — NUMERICAL APPLICATION," Ferrari, C., C.A.L. Report AF-814-A-2 (91 pages)

Through the application of the author's previously developed theory, several numerical examples are described which determine, within valid limits of linearized theory, the optimal contour of an annular duct for producing minimum external wave drag in supersonic flow.

"DISCUSSION OF PAPERS ON TURBULENT FLAME RESEARCH," Markstein, G. H., *Selected Combustion Problems*

Two papers presented at a combustion colloquium sponsored by the Advisory Group for Aeronautical Research and Development are discussed. Current theories of turbulent flame propagation are briefly described, and an alternate approach to the problem is suggested.

"EXPERIMENTAL INVESTIGATION OF INFLUENCE OF EDGE SHAPE ON THE AERODYNAMIC CHARACTERISTICS OF LOW-ASPECT-RATIO WINGS AT LOW SPEEDS," Bartlett, G. E. and Vidal, R. J., C.A.L. Report No. 62 (60 pages)

Results are presented for an experimental investigation of the influence of edge shape on the aerodynamic characteristics of a family of low-aspect-ratio wings, having straight trailing edges and taper ratios between zero and one.

"FLIGHT CONTROL SERVO DEVELOPMENT," Thayer, W. J. and Muzzey, C. L., C.A.L. Report 63 (62 pages)

This report discusses the development of a high performance position servo for actuating one of the flight control surfaces of a high-speed airplane.

"INVESTIGATION OF MEANS TO MAINTAIN ZERO ELECTRICAL CHARGE ON AIRCRAFT," Pelton, F. M., C.A.L. Report RA-766-P-10 (62 pages)

A description is given of the development and preliminary flight test of a system for maintaining an arbitrary net electrostatic charge on an aircraft (usually a zero net charge).

"MEASUREMENT OF THE DYNAMIC CHARACTERISTICS OF AN F-80 NOSE GEAR FOR STUDY OF SHIMMY PHENOMENA," Blazer, R. G. and Whitcomb, D. W., C.A.L. Report TE-665-F-4 (34 pages)

Results are presented of the measured response of an F-80 nose gear to a harmonic driving force applied laterally at the axle. Some measurements of the response of the nose gear to an impulse applied longitudinally and laterally at the axle location are also reported.

"ON THE FLOW BEHIND AN ATTACHED CURVED SHOCK," Pai, S. I., *Journal of the Aeronautical Sciences* (November 1952)

An investigation of the flow field behind a curved shock is discussed, including derivation of the characteristic differential equation of the stream function in the two-dimensional and axially-symmetrical cases.

"PURCHASING FOR RESEARCH AND DEVELOPMENT," Lindsay, E. M., *Purchasing* (March 1954)

The problems and requirements associated with purchasing for a research and development organization are discussed.

"THE ANALYSIS OF SOME GROUND TESTS OF THE LOW RANGE AIRSPEED INDICATOR FOR HELICOPTERS," Newell, F., C.A.L. Report IH-885-F-1 (28 pages)

A discussion is presented of the reduction and interpretation of the ground tests made on the C.A.L. low range airspeed indicator for helicopters.

"WING-BODY INTERFERENCE AT SUBSONIC AND SUPERSONIC SPEEDS. SURVEY AND NEW DEVELOPMENTS," Lawrence, H. R. and Flax, A. H., Annual Summer Meeting of the Institute of the Aeronautical Sciences, Los Angeles, Calif. (July 1953)

A critical survey is given of available theories on wing-body interference effects, simplified analysis methods for use in design, and experimental results, including some new developments based on recent work at C.A.L.